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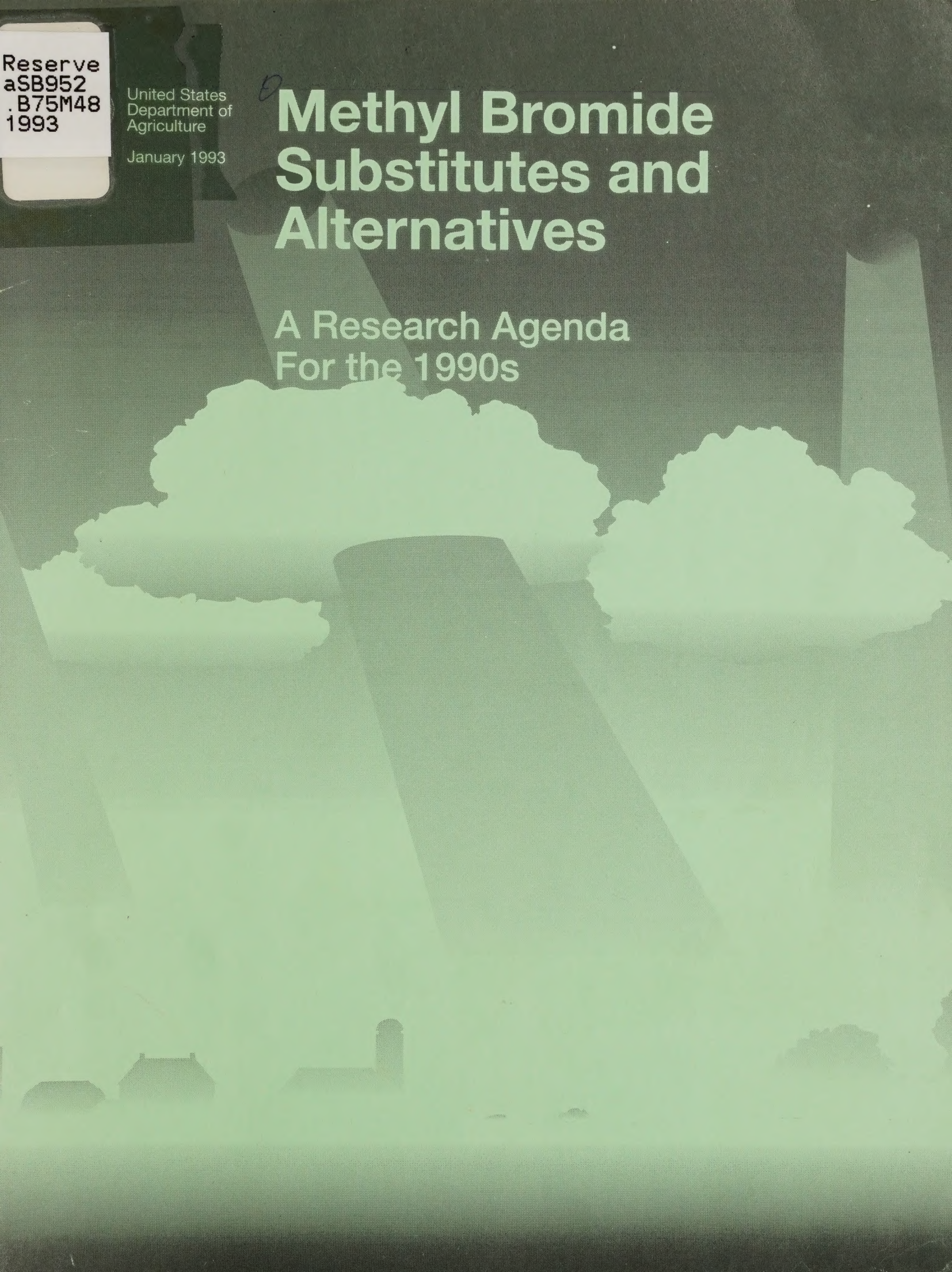
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Methyl Bromide Substitutes and Alternatives

A Research Agenda For the 1990s



**United States
Department of
Agriculture**

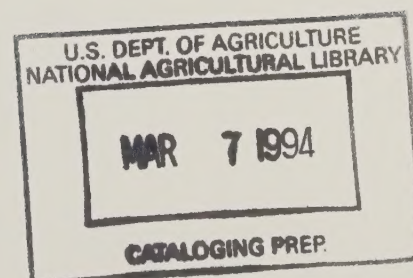


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Methyl Bromide Substitutes and Alternatives

A Research Agenda for the 1990's

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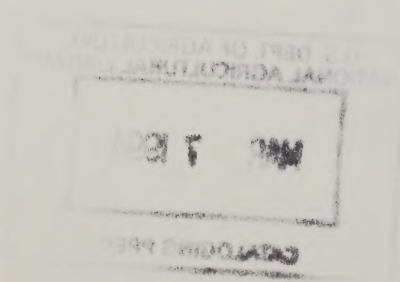


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Methyl Bromide Substitutes and Alternatives

A Research Agenda for the 1990's

I. Executive Summary

Methyl bromide has been identified as an ozone-depleting substance, with the potential to affect stratospheric ozone.

Anthropogenic uses have been implicated, but not substantiated, in about 30 percent of all atmospheric releases.

The U.S. Clean Air Act and the Montreal Protocol of the Vienna Convention require that any substance listed as ozone depleting be withdrawn from production and use in a specified time. While opportunities for specific exemptions may exist under the Montreal Protocol, the U.S. Clean Air Act, as amended, mandates elimination of listed ozone-depleting substances from production and use with no opportunity for special-use exemptions.

The major concern about the use of methyl bromide is its potential for escape into the atmosphere and its harmful effect on the stratospheric ozone layer. Although 85 percent of anthropogenic methyl bromide is used for soil fumigation, little data exist that describe its behavior in soil, or how much actually moves into the air above the soil. Further, little information exists that describes any atmospheric transport or degradation processes.

Because methyl bromide is listed as an ozone-depleting substance, USDA has developed this research agenda for replacing it or improving technologies to reduce or essentially eliminate emissions. This plan specifically sets out an agenda to accomplish the following objectives:

1. Establish methods and procedures to characterize and quantify methyl bromide emissions caused by applications to soils, postharvest protection systems, and commodity quarantine systems.
2. Develop technologies and procedures that would minimize or eliminate methyl bromide emissions from existing soil fumigation systems, postharvest protection systems, and commodity quarantine systems.
3. Evaluate existing and potential chemical substitutes for methyl bromide.
4. Evaluate existing and emerging nonchemical alternatives.

This agenda lists research needs associated with each of the above objectives and also includes an identification of priority for accomplishing each research need. Priority is defined, for the purpose of this agenda, as an index of how important the research is relative to other research activities, as well as how soon the results can be expected. This agenda has been developed to provide key policymakers and decisionmakers with the best scientific estimates of currently available alternatives and estimates of research needs to replace methyl bromide within the next 5 years.

Emission Research

The range of estimates suggest that anthropogenic methyl bromide accounts for 5 to 50 percent of the emitted methyl bromide with a best guess at 30 percent. These estimates have been made using the best available data. The problem is that very little scientifically credible data exist on which to base valid judgments. It is critical, therefore, to develop this data.

This research agenda provides an estimated need for about 33 scientists per year for the next 3 to 5 years, scaling back to five scientists for up to 10 years, to meet the priority needs for emission research.

Soil fumigation research needs include: measuring parameters that influence efficacy and control emissions from soil, measuring actual emissions from soil and quantifying factors that influence emissions (implied in the above but not specifically described are degradation measurements), and developing methods to reduce application rates to amounts needed for effective pest control.

Postharvest/quarantine research, much of which will require significant engineering input, includes: better systems for complete containment and recovery of methyl bromide (involving the design of postharvest / quarantine facilities and evaluating various vapor stripping technologies to remove methyl bromide from the vapor phase), new packaging, and, where needed, development of accurately calibrated requirements in quarantine procedures.

Chemical Substitutes

The scientific consensus is that no single chemical will achieve the broad spectrum activity of methyl bromide. However, there are some chemicals that afford some level of pest control with narrower activity ranges. Additionally, some treatments may result in lower crop yields and quality, the spread of pests during transplanting due to infested nursery stock, and increased costs.

Soil Fumigation. It is extremely unlikely that a new soil fumigant will be discovered, patented, and registered in the future. Most scientists agree that all promising and patentable compounds have been identified over the past 40 years. In the past 10 years, 248

new pesticides received registration somewhere in the world (99 herbicides, 74 insecticides, 60 fungicides, and 15 plant growth regulators). Five are soil insecticides with some degree of nematocidal activity. No new nematocides were registered between 1981 and 1991.

There are seven registered active ingredients that may offer some level of control as alternatives to methyl bromide. This agenda compares the performance of these fumigants with methyl bromide. Comparisons include: Chloropicrin, Telone, Metam sodium (Vapam, Busan), and Vorlex. Basamid and other nonvolatile nematocides, mostly organophosphates and carbamates, also are evaluated.

Clandosan 618, Enzone, and a variety of new nematode control concepts also are listed as being in early stages of field testing, especially by University of California researchers. This includes extracts of marigold and other plants; sesame chaff; antagonistic (allelopathic) cover crops, such as marigolds and poppies; and nematode pathogens, including bacteria and fungi.

Postharvest and quarantine. Various estimates indicate that 15-40 percent of the world's food supply is destroyed before consumption, and insects contribute significantly to this damage. Methyl bromide is favored because of its ease of use and the relatively short time required for fumigation (2-24 hours). The challenge is to find replacements with capabilities equal to those established by methyl bromide. Currently, postharvest researchers are conducting over \$5 million of research annually looking for new fumigants. Compounds that have been identified over the past 40 years with fumigant potential and registered for use have been withdrawn, canceled, and/or suspended from use.

In addition to fumigants, chemical and bacterial protectants are used in the control of insects. These may provide alternative treatments, however only in limited cases. A second group of novel chemicals is behavior-modifying chemicals that may be used in control or in surveillance of insects. Although significant research has been conducted, few of the alternatives will fully replace fumigation because of economic, logistic, engineering, phytotoxicity, and other considerations.

Substitute Chemical Research

Current estimates indicate that 42 scientists per year over the next 5 years will be needed with 19 scientists per year required for the next 10 years to meet the priority research needs for substitute chemicals.

Soil fumigation.

- Accelerate registration/re-registration of existing chemical fumigants.
- Improve efficiency and effectiveness of chemical substitutes.
- Conduct chemical irrigation management practice studies to increase residence time of chemicals in the root zone.
- Conduct studies to measure the permeability of various plastic mulch films.
- Investigate integrated cropping systems to incorporate new technologies, maximize fumigant efficacy, reduce the rate of atmospheric emission of methyl bromide used for multiple pest control in various cropping systems, maximize root zone retention of nonfumigant nematocides, and assess the long-term economic impacts of phasing out fumigation uses of methyl bromide in U.S. agriculture.

Postharvest/quarantine. Significant research will be necessary to bring the available residual protectant materials to the point where they could substantially reduce fumigant use. Several new-generation chemicals such as chitin inhibitors, insect growth regulators, protease inhibitors, and hormone inhibitor /mimics show promise. Basic research is necessary on pest biology to determine activity sites for applications of new classes of chemical fumigants and growth regulators, such as methoprene, and to determine the efficacy and application methods needed to achieve quarantine security. Finally, data from the 1940's to the 1980's should be reevaluated to determine if further investigation is warranted.

Nonchemical Substitute Research

Currently no nonchemical substitute for methyl bromide exists for all problems including weeds, nematodes, insects, fungi, bacteria, and viruses. Host-plant resistance offers the potential for the most effective biologically based strategy for managing plant pests. Microbial biocontrol agents also are available to control a few pathogens. Noncultural technologies, such as heat and steam, are useful for greenhouse and small-scale applications in the United States, but are not applicable for large fields.

Nonchemical Research Needs

105 scientists per year for the next 5 years will be required to begin to meet the needs for new quarantine protocols to replace methyl bromide. For the first 3 years, at least 70 of the 105 scientists are needed for accelerated quarantine protocol work to provide time to get alternative protocols approved before the year 2000.

Soil fumigation. Increased research emphasis will be needed to:

- develop biological control technologies for *Verticillium* and *Fusarium* wilt, plant-parasitic nematodes, and soilborne fungal diseases.
- develop genetically engineered vegetable crops.
- develop biological control agents for introduction into forest tree nursery seed beds to control damping-off fungi.
- develop fungi and insects destructive to weeds, for biological control of major problem weeds.
- develop antagonistic micro-organisms that can be associated with plastic mulches to enhance antagonist activity towards pathogenic fungi and nematodes.
- enhance application of biological, cultural, and disease resistance technologies and strategies for use with Integrated Pest Management.

-
- enhance understanding of host/parasite relations in nematode and pathogen/host systems.
 - strengthen studies on soil ecology of fungal pathogens and parasitic nematodes as well as antagonistic biological control agents.

Postharvest/quarantine. Scientists will need to develop many methods that are specific to each commodity or group. Often their influence on specific cultivars also will need to be determined. This agenda focuses only on development and certification of quarantine protocols. It does not consider the time delays and problems associated with certification of quarantine facilities at the shipping point.

Nonchemical Quarantine Research

Research needs are identified by treatment categories most suitable for each of the following commodities: propagative plant material and cut flowers; green leafy vegetables; root vegetables; dried fruits and nuts; tropical fruits; deciduous fruits and berries; citrus; grains, peanuts, legumes and beans; melons and fruits eaten as vegetables; and nonfood (tobacco, packing material, wood) products. The treatment categories currently include: heat, cold, ionizing radiation, controlled atmospheres, microbials, parasites and predators, phytosanitation, integrated system approaches, insect-resistant packaging, chemical protectants, and mechanical impact technologies.

Methyl Bromide Substitutes and Alternatives

A Research Agenda for the 1990's

II. Introduction

This research agenda was developed recognizing that uses of methyl bromide in agriculture and forestry will be significantly reduced in the future, after implementation of the U.S. Clean Air Act, as amended, and 1992 amendments to the Montreal Protocol of the Vienna Convention.

Recognizing the issues at hand, and the time required to produce alternative technologies and substitute chemicals, the U. S. Department of Agriculture (USDA) began developing a strategic plan and research agenda in February 1992. This agenda will aid key decision makers in determining the allocation of research efforts to meet the impending needs for new technologies and substitutes for methyl bromide.

Methyl bromide has been identified as an ozone-depleting substance, with the potential to affect stratospheric ozone. Anthropogenic uses have been implicated, but not substantiated, to account for approximately 30 percent of the atmospheric releases. Most methyl bromide uses are attributed to agriculture, although significant other sources may exist (for example, fuel combustion and inadvertent production). Currently the U. S. agriculture and forestry uses include soil fumigation (disease, weed, insect, and nematode control), protection from postharvest loss, quarantine, and special fumigant uses.

The U.S. Clean Air Act, as amended, and the Montreal Protocol require that any substance listed as an ozone-depleting substance be withdrawn from production and use. While some opportunities for special

use exemptions may exist or have the potential to exist under the Montreal Protocol, the U.S. Clean Air Act, as amended, mandates the elimination from production and use with no current opportunities for special use exemptions. The 1992 amendments to the Montreal Protocol listed methyl bromide as a controlled substance with an ozone-depleting potential (ODP) of 0.7 and established a freeze in production at 1991 levels by 1995, except for quarantine and pre-shipment uses. A nonbinding resolution was passed to make every effort to reduce emissions of and to recover, recycle, and reclaim methyl bromide.

Recognizing the critical issues facing American agriculture and forestry, USDA hosted a workshop to identify research needs and initiate a research agenda for developing alternative technologies and substitutes for methyl bromide in soil fumigation, postharvest protection, and quarantine. Thirty-five scientists from USDA's Agricultural Research Service, State Agricultural Experiment Stations, private industry, and the U.S. Environmental Protection Agency (EPA) participated in this workshop. The results of the USDA workshop formed the basic framework and guidance for this research agenda.

The participants used their own expertise, and referred to the most comprehensive assessments available at the time. These included: (1) the draft National Agricultural Pesticide Impacts Assessment Program (NAPIAP) assessment of methyl bromide uses and (2) the United Nations Environment Program

(UNEP) science and technology interim assessments of methyl bromide, conducted in May 1992. The USDA workshop specifically noted that in the UNEP Assessment Reports, the availability of substitutes by 1997 for methyl bromide was overestimated. Current estimates range from 25 to 30 percent availability of substitutes by 1997.

Development of this research agenda does not stop with completion and delivery of this document. It is a living document that must be continually reviewed and revised as research priorities shift. There also is a need to develop a technology transfer agenda that identifies users, establishes methods to move information quickly, and provides user contact points.

III. Research Agenda

This is a research agenda for replacing methyl bromide or improving technologies to reduce or essentially eliminate methyl bromide emissions. The goals are to accomplish the following objectives:

1. Establish methods and procedures to characterize and quantify methyl bromide emissions due to applications to soils, postharvest protection systems, and commodity quarantine systems. These methods and quantification procedures are necessary to firmly establish the baseline of emissions from agriculture and forestry uses. This information is needed because the Montreal Protocol has special use exemptions; a nonbinding agreement to reduce methyl bromide emissions; and mandates for science, technology, and economic assessments over the next 2 years. The U. S. Clean Air Act, as amended, currently grants no exemptions for either special uses or emission reduction. Baseline data on emissions, however, will be needed if there should be interest in the future to seek such exemptions to the U.S. Clean Air Act.
2. Develop technologies and procedures that would minimize or eliminate methyl bromide emissions from existing soil fumigation systems, postharvest protection systems, and commodity quarantine systems (assuming that between 1993 and 2000 special use exemptions can be placed in the U.S. Clean Air Act, as amended).
3. Evaluate existing and potential chemical substitutes for methyl bromide for soil fumigation and postharvest protection/quarantine; identify those uses lacking substitutes; and assess registration needs, efficacy, weaknesses, and additional testing.

4. Evaluate existing and emerging nonchemical alternatives for control of soilborne and postharvest protection/quarantine pests, and identification of those uses requiring additional research and development.

Each section of this agenda lists research needs and includes an identification of priorities in terms of how important the research is relative to other research activities as well as how quickly the results are needed. Therefore, priority is defined, for this agenda, as identification of research in terms of results required in the *short term* (1 to 2 years), *medium term* (2 to 5 years), or *long term* (more than 5 years). Each research activity also includes an estimate of *research scientists per year* needed to accomplish the priority plus the *additional research* requirements over and above the annual cost of a *scientist year*. The annual cost of a *scientist year* is currently set at \$250,000. A *scientist year* is the basic cost to support a research scientist for 1 research year, including salaries for technicians, secretarial and other support, facilities rental cost, and normal research equipment and supplies. *Additional resources* would include high-cost special instruments and laboratories or facilities, as well as supplemental contracts for research.

Structure of the Plan

The plan contains three major research areas:

- Methyl bromide emissions research (focusing on objectives 1 & 2).
- Chemical alternatives research (focusing on objective 3).
- Nonchemical alternatives research (focusing on objective 4).

Each of these research areas is subdivided into (a) soil fumigation research needs and (b) postharvest protection/quarantine research needs.

IV. Methyl Bromide Emissions Research

Introduction

Methyl bromide is used to control numerous postharvest pests in soils and in fruit and vegetable commodities. Few substitute materials have been developed that effectively control bacteria, fungi, insects, and weeds in soil and the pests that degrade these products postharvest. In terms of quarantine uses, methyl bromide fumigation is frequently required.

The major concern about the use of methyl bromide is its potential for escape into the atmosphere and its harmful effect on the stratospheric ozone layer. Estimates suggest that anthropogenic methyl bromide accounts for 5 to 50 percent of the emitted methyl bromide. These estimates have been made using the best available data. The problem is that very little scientifically credible data exist on which to base valid judgments. Although 85 percent of anthropogenic methyl bromide is used for soil fumigation, little data exist that describe its behavior in soil and how much actually moves into the air above the soil. Further, little information exists that describes any atmospheric transport or degradation processes. If it can be demonstrated that most methyl bromide comes from natural sources, or that little actually moves into the atmosphere after soil treatment, or that little will move into the atmosphere through use of superior management practices, or that one can demonstrate that the emitted methyl bromide ends up in vegetative or ocean sinks and does not move to the stratosphere, then concern about emission of methyl bromide would be significantly reduced. Adequate scientific data is needed to validate the computed ozone-depleting potential (ODP) of methyl bromide, either reducing its current value or substantiating the current estimate. It is critical, therefore, to develop this data.

Similar issues need to be studied for quarantine and postharvest uses of methyl bromide, and for many of the same reasons. The technology exists to reduce emissions from these uses, but considerable engineering research, design, and money will be required to implement it.

The most direct and nondisruptive solution to alleviate atmospheric release of methyl bromide would be to reduce or eliminate emissions into the atmosphere. Thus research should provide data on reduction of doses, recycling methods, and methods to reduce or eliminate emissions. The technical and economic feasibility of reducing or eliminating emissions will depend on tolerance levels set by the EPA. Use of these technologies is one of the few research avenues that would be least disruptive to quarantine treatment schedules now in place.

Recommendations on Research Needs for Emission Research

Soil Fumigation

1. Measure parameters that influence efficacy and control emissions from soil. To evaluate these one must study and quantify dosages that control pests, and factors that affect movement/transport and fate in soil. For movement/transport, these include convection, diffusion, sorption, density, dissolution in water, boundaries, and depth of injection. These include all factors influencing movement / transport, such as hydrolysis, density, vapor pressure, soil organic matter content, tarping procedures, temperature, soil moisture, dosage, soil particle, pore, and space size.
 - Scientists/year: 12.0 (2-3 years) (\$250,000/ scientist year).
 - Priority: short term (work to start immediately).
 - Additional resources: \$500,000 per year. Much of this work is in progress and is funded by USDA/NAPIAP.
2. Measure actual emissions from soil and quantify factors that influence emissions. This includes the time tarps/soil covers are in place, effect of photosensitizers or other methyl bromide degraders on the tarps, and the potential effect of barometric pressure changes. Measure levels of methyl bro-

mid at various heights in the troposphere (0-18 km). Evaluate the influence of various sinks on emissions and on methyl bromide transport to upper levels of the troposphere (vegetative or other organic matter as soil amendments as a cover crop, forested areas downwind, lakes, oceans and other bodies of water, sorption of methyl bromide on particulate matter, etc.).

- Scientists/year: 2.0 (\$250,000/scientist year).
- Priority: short term (preliminary phase - 3 years; full-scale phase - 3 years).
- Additional resources: \$100,000 per year (NAPIAP is contributing funds).

Note: Both 1 and 2, above, will provide data to refine and test predictive models.

3. Implied in the above but not specifically described are degradation measurements. Hydrolytic and microbial degradation rates, factors influencing degradation (soil water content, concentrations, organic matter, pH, etc.) and degradation products need to be determined.

- Scientists/year: 5.0 (3-5 years) (\$250,000/scientist year).
- Priority: short term.
- Additional resources: \$100,000 per year (NAPIAP is contributing funds).

4. Methods to reduce application rates to amounts needed for effective pest control will require evaluation of the specific roles of factors that determine minimum application rates (water content, organic matter, boundaries, tarps, etc.). Methods to minimize losses during and after application require evaluation of parameters, including injection depth, better tarps or film, longer tarping periods, drip-irrigation applications, timing of fumigation (spring, summer, fall), soil amendments or other covers (activated carbon, or other soil amendments, cover crops, etc.).

- Scientists/year: 5.0 (5-10 years) (\$250,000/scientist year).
- Priority: medium term.
- Additional resources: \$500,000 per year.

Postharvest/Quarantine

Note: Much of this research will require significant engineering input.

1. Redesigned systems are needed for complete containment and recovery of methyl bromide. This research and development program must begin immediately. The program will include use of containers specifically designed for fumigation; retrofitting of existing chambers; designing new chambers; or development of recovery, recycling and destruction systems for methyl bromide (activated charcoal, sodium hydroxide scrub), and technologies to separate methyl bromide from other gases (for example membranes or zeolite filters).

- Design studies of postharvest/quarantine facilities, new and upgrades of existing buildings. Design targets should be facilities capable of using minimal free space and controlled commodity passage to minimize methyl bromide loss from the facility,
- Evaluate various vapor stripping technologies to remove methyl bromide from the vapor phase in the facility before commodities exit.

Parts a and b above can be carried out simultaneously and independently. The potential for Cooperative Research and Development Agreements (CRADA's) between the private sector and the Federal laboratories is extremely high in this area.

- Scientists/year: 2.0 (2 - 3 years) (\$250,000/scientist year).
- Priority: short term (work is required to start immediately).
- Additional resources: \$200,000 per year.

-
2. New packaging. When products are placed in packaging after fumigation, the packaging should be designed to sorb emitted methyl bromide as it comes out of the product. If the product is fumigated in packaging, develop a package that will not sorb methyl bromide.
 - Scientists/year: 1.0 (2-3 years) (\$250,000/scientist year).
 - Priority: medium term.
 - Additional resources: \$50,000 per year.
 3. Develop accurately calibrated requirements, where they do not already exist, in quarantine procedures. Develop fumigation concentrations that will meet quarantine standards with methyl bromide alone or in combination with other fumigants.
 - Scientists/year: 2.0 (2-3 years) (\$250,000/scientist year).
 - Priority: short to medium term.
 - Additional resources: \$100,000 per year.
 4. Determine the exact fate of methyl bromide in products. Measure the quantity of methyl bromide that goes into the system, measure that which comes out, and that which stays in the product or is degraded. Determine the residual on products from altering exposure times versus dosages (concentrations) to reduce sorption.
 - Scientists/year: 2.0 (1-2 years) (\$250,000/scientist year).
 - Priority: medium term.
 - Additional resources: \$100,000.
 5. Measure residual level in product and losses after fumigation. It is not possible to completely eliminate emissions from treated products. Measure loss of methyl bromide in secondary processing of treated products, for example, manufacturing using methyl bromide treated logs. Develop the concept of de-minimis levels.
 - Scientists/year: 2.0 (2-3 years) (\$250,000/scientist year).
 - Priority: short to medium term.
 - Additional resources: \$100,000 per year.

V. Chemical Alternatives Research

Soil Fumigation

Methyl bromide has the capacity to control insects, plant pathogens, nematodes and weeds when applied in the soil. The consensus is that no single chemical will equivalently replace the broad spectrum activity of methyl bromide. Some chemicals are available that afford reduced pest control with narrower activity ranges. Some treatments may result in lower crop yields, lower quality, the spread of pests during transplanting of infested nursery stock, and increased costs. Further, methyl bromide has the advantage of allowing intensive, 2 subsequent year, cropping systems from a single soil fumigant treatment that would be reduced or lost with substitute chemicals.

It is extremely unlikely that a new soil fumigant will be discovered, patented, and registered in the future. An effective fumigant must have certain chemical properties (namely, a relatively small molecule with a high vapor pressure and a biologically active component such as a chlorine or bromine atom). This entire area of chemistry was thoroughly investigated from the 1940's through the 1950's, and scientists believe that all promising and patentable compounds were identified during that period. It is not likely that a chemical company will invest \$20 to \$40 million dollars necessary to register a product that is not patentable. This is borne out by the fact that no new fumigants have been registered in many years.

New nonfumigant nematocide products are unlikely to be developed. Wood/Mackenzie Ltd., a British company that tracks trends in the chemical industry, recently completed a summary of new pesticides registered between 1981 and 1991. A total of 248 new pesticides received registration somewhere in the world during this period (99 herbicides, 74 insecticides, 60 fungicides, and 15 plant growth regulators). Five of these are soil insecticides with some degree of nematocidal activity. No new nematocides were registered between 1981 and 1991.

Table 1 lists several nematocides and compares the performance of these fumigants with methyl bromide.

Assessment of Available Soil Fumigants

There are seven registered active ingredients that may offer some level of control as alternatives to methyl bromide. Two of these (chloropicrin and 1,3-D) have sufficient volatility to be considered soil fumigants. The others are essentially non-fumigant, contact nematocides which must be incorporated mechanically or with water in order to reach the target pests.

Chloropicrin: An effective insecticide and fungicide, but not as effective as methyl bromide for nematode control. The chemical has a very pungent odor (it is tear gas), and it can be very unpleasant or even hazardous to handle.

Chloropicrin/Methyl Bromide (67/33):

Formulations of 67 percent chloropicrin and 33 percent methyl bromide are effective because of the enhanced activity achieved by using two chemicals in combination. For plant diseases, the 67/33 formulation is superior to methyl bromide used alone. The overall performance is quite close to, and in some cases better than, that of methyl bromide.

1,3-Dichloropropene (Telone): In terms of nematode control, 1,3-D is comparable to methyl bromide. Since it is much less volatile, tarping is not necessary. Because tarping is not required and less is generally applied per acre, 1,3-D is affordable for crops such as potatoes, cotton, sugar beets, peanuts, and certain vegetables for which the cost of methyl bromide would be prohibitive. 1,3-D does not provide comparable weed seed or disease control.

Metam sodium (Vapam, Busan): Metam sodium provides good soil insect control and some level of control for fungi, weeds, and nematodes, but not with the efficacy of methyl bromide. For more effective control, application through an irrigation system (usually a

sprinkler system) is preferable. Further, it requires an unusually long waiting period between application and planting for some crops. It is usually applied in early spring or fall. Because of its time of application, particularly in the fall when applied under plastic mulch, labor and materials costs can be excessive.

Vorlex: Vorlex is a mixture of 20 percent methyl isothiocyanate (MITC) and 40 percent 1,3-Dichloropropene. With the loss of methyl bromide, attempts to use other chemical means of soil pest management compatible with current production practices and available application equipment will likely be adopted to achieve broad spectrum soil pest control (table 2). Vorlex was the only chemical alternative identified that could provide near equivalent broad spectrum pest control. However, at Vorlex application rates which would provide similar levels of pest control (35 gallons per acre - label rate for mineral soils), average production losses of 5 - 10 percent are likely to occur for most vegetable crops. The grower also would experience a 60- to 70-percent increase in pest control costs. As is the problem with other perceived chemical alternatives, the slower degradation and diffusiveness of Vorlex products in soil also will require a longer treatment and aeration period, which in turn will contribute to unexpected planting delays and increased risk of crop phytotoxicity and risk of recontamination of soil.

The registrant requested EPA to cancel its re-registration process for Vorlex effective August 31, 1992.

Other key chemical alternatives, most notably Basamid and Telone, are currently under special review or may have lengthy delays in final food crop registrations.

Status of Nonvolatile Nematocides

Basamid (Dazomet - tetrahydro-3,5-dimethyl-1,2,5-thiadiazine-2-thione): The granular form is a microgranular preparation and contains 98 percent Basamid. Since the compound consists of carbon, nitrogen, sulfur, and hydrogen, it has no ozone-depleting potential.

Being a solid material, Basamid will stay inert until after application, thereby minimizing worker expo-

sure. Like all other chemical soil sterilants, it must be incorporated into very moist soil where it degrades, releasing the active ingredients, and acts against nematodes, fungi, bacteria, insects, and weeds.

Covering the soil immediately after application (tarping) increases efficacy by maintaining soil moisture and temperature, and ensures an environmentally sound fate of the product (groundwater protection from release of volatiles). The ease of Basamid application offers a wide range of different techniques and allows adaptations to practical needs from small- to large-scale uses.

The end products of Basamid degradation and metabolism in the soil are bicarbonate, and naturally occurring nitrogen and sulfur compounds that can be regarded as fertilizer. In a lysimeter study conducted over 2 years in Germany under outdoor conditions, it could be demonstrated that no residues of toxicological relevance occurred in treated soil or in water that percolated through the soil. In the United States, Basamid currently is registered for use on nonfood crops only (tobacco, ornamentals, tree nurseries, turf, etc.). Data for food uses are in preparation, but it is estimated that registration is more than 3 years away.

Other nematocides, mostly organophosphates and carbamates, are registered for specialty uses only:

Phorate is widely used as an insecticide, but because of its high mammalian toxicity and the high dosage levels required for nematocidal activity, it has only one registered nematocidal use- Easter lilies in the Pacific Northwest.

Dematon is registered as a nematocide for use on four ornamental crops.

Diazinon is a general-use insecticide, but as a nematocide, it is registered and marketed under the trade name Sarolex for use on ornamentals and turf grasses.

Terbufos is registered as a nematocide for use on corn, sorghum, and sugar beets.

TH285-N (Bunema) is registered as a nematocide for use on southern warm-season turf grasses.

Also available are three other organophosphates (ethroprop, fensulfothion, and fenamiphos) and three

Table 1
Effectiveness of Other Chemical Fumigants
Compared to Methyl Bromide

	Methyl Bromide	Chloropicrin	Methyl Bromide/ Chloropicrin (67/33)	1,3-D	1,3-D/Chloropicrin (83/17)	Basamid	Metam Sodium	Vorlex
Control Activity								
Insects	0	0	0	–	0	0	0	0
Nematodes	0	–	0	0	0	–	–	0
Plant diseases	0	0	+	–	0	–	–	<u>0</u>
Weeds	0	–	0	–	–	–	–	<u>0</u>
Ease of Use	0	0	0	+	0	<u>0</u>	–	0
Time for Treatment	0	<u>0</u>	<u>0</u>	–	–	–	–	–
Compatability ¹	0	0	0	0	0	–	±	0
Treatment Costs	0	±	±	+	–	–	–	–
Crop Yield	0	–	+	–	0	–	–	<u>0</u>
Crop Quality	0	–	0	–	0	–	–	<u>0</u>
Environmental Effects	0	0	0	0	0	+	+	0
Worker Safety	0	0	0	+	+	+	+	+
Availability	0	0	0	–	–	–	0	–
Registration Status								
Food Crops	0	+	0	0	0	–	0	?
Nonfood Crops	0	0	0	0	0	0	0	?

Comments:

0 = Similar to Methyl Bromide
 – = Not as good as Methyl Bromide
 + = Better than Methyl Bromide
 ? = Unknown

¹With current production systems

carbamates (aldicarb, carbofuran, and oxamyl) which are registered as nematocides for uses that include application at preplanting, at the time of planting, and postplanting.

Organophosphates and carbamates may be hazardous to humans and animals during and after application if proper safety precautions are not used. These nonvolatile materials are usually less effective against a wide range of nematodes than are other soil fumigants. Unlike the soil fumigant - which volatilize and move through the soil as a gas after being injected in, or drenched on-nonvolatile materials must be placed at or near their targets. This requirement demands precise application and soil preparation, which is not always easily achieved. Under certain conditions, carbamate nematocides may cause environmental problems because of their persistence in the soil and their ability to seep or leach through soil and contaminate ground water.

Fenamiphos has been used in tank mixes with metalaxyl (a fungicide) and herbicides to control the root-knot/black shank complex and weeds on flue-cured tobacco, but the results from these treatments have not been compared with methyl bromide treatments.

It also has been noted that consistent root-knot nematode control on peanut plants with at-plant and at-peg applications of fosthiazate compared to other registered alternatives (preplant -1,3-D, or at-plant and at-peg applications of fenamiphos or ethroprop). Fosthiazate is an organophosphate permitted for experimental preplant or at-plant application for the major genera of nematodes attacking tomatoes and tobacco.

Potential Nematocides in Development

Clandosan 618 chitin/protein complex (IGENE Biotechnology, Inc.) is a blend of chitin and proteins (derived from crab and shrimp shells), urea, and an organic buffer. When mixed with soil, it is said to stimulate the growth of soil organisms, including actinomycetes, bacteria, and fungi, which produce chitinases and ureases in response to the availability of these substrates. Nematode eggs and shells contain chitin complexes or very similar components and can be affected by these enzymes. Clandosan also has fertilizer effects, due to the urea present in the formulation.

Clandosan has EPA registration for greenhouse, turf, ornamentals, and various agricultural crops. It has not been approved for use in California.

An increase in soil chitinase activity and an associated suppression of nematode populations have been demonstrated in the laboratory, greenhouse, and field microplot experiments, following addition of chitin in various forms. Several publications in the nematology literature document these effects. They occur only in immediate proximity to the substrate, so very thorough incorporation is necessary.

One common theme in all the research is the requirement for extremely large amounts of material. In a field situation, the grower would have to apply 1 to 3 tons per acre on a broadcast basis. Even if this would result in consistent performance (which has not been demonstrated), the logistics of moving and applying this large amount of material makes it totally impractical in the vast majority of situations. It may be just within economic viability for specific, very high cash crops, greenhouses, ornamentals, and turf grass, in areas near the chitin sources. Coastal areas near the Gulf of Mexico and the eastern seaboard are the only U. S. areas where this concept has any chance of gaining limited commercial success. Some degree of patent protection may be available for specific formulations and processes.

Clandosan has a very favorable toxicity profile. While it is an eye irritant, and skin irritation and possible allergic reactions have been reported, no significant handling precautions or equipment are required.

Enzone (GY-81:sodium tetrathiocarbonate) is composed of calcium and sodium tetrathiocarbonate salts. Its biological activity is caused by the hydrolysis product, carbon disulfide. It is a broad spectrum biocide, active on fungi, insects, and nematodes. In some ways, it is similar to metam-sodium, because large amounts must be applied, thoroughly incorporated into the soil, and activated with water. Field results have been inconsistent and unpredictable, but promising enough to justify further work.

Unocal is developing data for preplant nematode control in annual crops, preplant and postplant fungus, insect, and nematode control in perennial tree and vine crops. The most promising projects to date involve *Phytophthora* root rot control in citrus and *Phylloxera* (root aphid) control in grapes.

Unocal requested an exemption from the plant metabolism and crop residue data requirements, on the grounds that the principal metabolites (carbonate, or bicarbonate, and hydrogen sulfide) are plant nutrients. However, EPA has decided to require these studies. Registrations may not be granted until these studies are completed. When they are, Unocal expects the first registrations to be for post-plant applications in several tree and vine crops, for nematode and *Phylloxera* control. In the mean time, they have been testing the products in large Experimental Use Permit (EUP) programs, particularly in California.

Other Nematode Control Agents

A variety of new nematode control concepts are in early stages of field testing, especially by University of California researchers. This includes extracts of marigold and other plants; sesame chaff; antagonistic (allelopathic) cover crops, such as marigolds and poppies; and nematode pathogens, including bacteria and fungi. In general, results have been inconsistent to negative. Some of these may justify further research. If any of these reach commercialization, it will be no earlier than 1998.

Postharvest and Quarantine Commodity Fumigation

Fumigation is often the method of choice to disinfest stored products and fresh commodities. Methyl bromide makes up a large component of these fumigations. Various estimates indicate that 15-40 percent of the world's food supply is destroyed before consumption, and insects contribute significantly to this damage. Methyl bromide is favored because of its ease of use and the relatively short time required for fumigation (2-24 hours). Some commodities, however, may become infested and might require more than one fumigation, not only to protect the commodity from insect pests but also to prevent secondary effects caused by fungi or other micro-organisms. Often these problems are related to metabolic water released by insects, which provides the physical environment nec-

essary for the growth of these organisms and production of mycotoxins. The challenge is to find replacements with capabilities equal to those established by methyl bromide. Currently postharvest researchers are conducting over \$5 million in research annually looking for new fumigants.

Postharvest uses of methyl bromide can be divided into quarantine and commodity protection fumigations. Quarantine treatments are designed to exclude specific pests from countries not having the pests. Such treatments are required by the importing country and methyl bromide is predominately used. Postharvest protection is essential for many high economic value commodities. These commodities often gain greater economic value before export of value added by processing.

Methyl bromide is also the primary fumigant used to disinfest grain milling and processing facilities. No other fumigant is sufficiently toxic, fast acting, or non-corrosive to structural components to meet this need. Table 2 compares the performance of existing fumigant alternatives for quarantine.

The limited number of chemicals that fit the criteria were screened in the 1940's to 1980's with limited success. The compounds identified as having fumigant potential and subsequently registered for use have been withdrawn, canceled, and/or suspended from use (e.g., carbon tetrachloride, trichloroethylene, ethylene dibromide). There are no other chemicals available that provide the physical and chemical characteristics that would make them as useful for alternative commodity treatments, including quarantine treatments.

The only other fumigant available for edible products is phosphine. The two major factors that prevent its use as a substitute for methyl bromide are (1) that the time required to attain 100 percent kill is 3-7 days as compared with 2-48 hours for methyl bromide, and (2) that phosphine is phytotoxic to some fresh commodities currently treated with methyl bromide. In addition, phosphine cannot be used in situations where it comes into contact with copper (such as wires) or its alloys (such as brass) because it is corrosive to the elements copper, silver, and gold.

Table 2
Comparison of Quarantine and Postharvest Control Treatments

	Methyl Bromide	Phosphine	Sulfuryl Fluoride	Ethylene Oxide	Hydrogen Cyanide
Insect Control	0	–	–	0	–
Nematodes	0	–	–	0	n/a
Ease of Use	0	+	0	–	–
Time for Treatment	0	–	0	0	0
Comparing with Present Production Systems	0	±	0**	–	–
Treatment Cost	0	–	–	–	–
Commodity Quality	0	±	–	–	–
Environmental Effects	0	?	0	–	+
Worker Safety	0	–	0	–	–
Availability	0	0	–	–	–
Registration Status on Food Crops	0	±	–	–*	–
Registration Status on Non-food crops	0	±	–	–	–

+ = Better than Methyl Bromide

– = Not as good as Methyl Bromide

± = Same as Methyl Bromide

? = Unknown

* *Spices only*

** *Corrosive to copper and other alloys*

Nonfumigant Chemicals and Biological Controls

In addition to fumigants, chemical and bacterial protectants are used in control of insects and may provide alternative treatments for limited cases only.

Chemicals and bacteria already registered for grain, commodities, and/or storage facilities where methyl bromide may be used include malathion, actellic, rel-dan, *Bacillus thuringiensis* (Bt), synergized pyrethrins, diatomaceous earth, and methoprene. Considerable insect resistance to methoprene has been reported.

A second group of novel chemicals is behavior modifying chemicals that may be used in control or in surveillance of insects. All the traditional or new chemicals are not designed to disinfest already-infested commodities but rather to prevent infestations from developing. It is important to note that these chemicals could reduce the need to use a fumigant such as methyl bromide, but will not replace it as a fumigant. These include insect growth inhibitors, chitin inhibitors, hormone mimics, and protease inhibitors.

With some exceptions in fresh commodities, fumigations have provided for economically disinfecting commodities to meet the quarantine demands of international trade. Although significant research has been conducted, few of the alternatives will fully replace fumigation because of economic, logistic, engineering, phytotoxicity, and other considerations. Because most commodity industries significantly depend on international markets for the sale of their products, new treatment procedures must be as nondisruptive as possible to these agricultural industries. Some alternatives will not be appropriate because of economics, availability, sensitivity of the commodity, efficacy limitations, etc. The criteria for development and use as an alternative commodity or quarantine treatment depend on many factors (table 3) and will depend on the level of training and skills available both in this country and countries exporting commodities to the U. S.

Recommendations on Research Needs for Substitute Chemicals

Soil Fumigation

1. Accelerate registration/re-registration of existing chemical fumigants such as 1,3-D, Basamid (Dazomet), metam sodium, and Vorlex . Establish and maintain liaison with EPA, manufacturers, and grower groups.
 - Scientists/year: 3.0 (3-10 years) (\$250,000/scientist year).
 - Priority: medium term.
 - Additional resources: \$250,000.
2. Improve efficiency and effectiveness of chemical substitutes.
 - Study reduced rates and combination treatments.
 - Define treatment thresholds.
 - Develop more efficient application methods such as emission mitigation studies
 - Scientists/year: 2.0 (2-3 years) (\$250,000/scientist year).
 - Priority: medium term.
 - Additional resources: \$500,000-to include air monitoring equipment and improved application equipment.
3. Conduct studies on chemical irrigation management practices to increase root zone residence time exposure to chemicals.
 - Scientists/year: 2.0 (3-7 years) (\$250,000/scientist year).
 - Priority: medium term.
 - Additional resources: \$250,000.
4. Conduct studies to measure the permeability of various plastic mulch films.
 - Scientists/year: 2.0 (\$250,000/scientist year).
 - Priority: short term.
 - Additional resources: \$500,000.

-
5. Investigate integrated cropping systems to incorporate new technologies - chemical fumigants, nonvolatile chemicals, and new application methods-and conduct studies on the enhancement of existing technologies. Research on multiple cropping systems requires several years, because it may take 3 years to complete one cycle and it is advisable to repeat the cycle at least once to determine if the system is sustainable.
 - Scientists/year: 2.0 (5-10 years) (\$250,000/scientist year).
 - Priority: medium term.
 - Additional resources: \$200,000.
 6. Factors influencing soil pest control with metam sodium (this is designed to include all methyl isothiocyanate (MITC) generators i.e., Basamid, Dazomet) and 1,3-Dichloropropene in vegetable cropping systems. To maximize fumigant efficacy, a clearer understanding of application delivery system, the impacts of soil temperature, moisture, and texture (environmental conditions), fumigant concentration and differential toxicity, duration of activity and pest exposure, and final soil distribution is required. Since no new fumigants are likely to appear in the foreseeable future, basic research is needed to improve existing application delivery system technology, enhance the consistency of pesticide performance, identify product limitations, and support product re-registrations.
 - Scientists/ year: 3.0 (3-4 years) (\$250,000/ scientist year).
 - Priority: medium term.
 - Additional resources: \$300,000.
 7. Crop production management strategies for maximizing root zone retention of nonfumigant nematocides. Inconsistencies with regard to the level of pest control that is achieved with nonfumigant nematocides are related primarily to changes in pesticide concentration, distribution, microbial degradation, and soil residence duration. At present very little information is available regarding optimal management strategies to maximize nematode control, crop yield, and root zone retention of soil-applied nematocides. Considerably more information is needed regarding pesticide distribution, movement, and longevity within different soils, particularly with respect to irrigation frequency and duration, or rainfall events. The use of drip irrigation systems for the delivery of nematocides coupled with use of plastic mulch covers are other specific technologies about which insufficient information currently exists. An effective pesticide dosage concept coupled with computer simulation approaches relating soil pesticide concentration and exposure time to levels of nematode control also needs to be developed.
 - Scientists/ year: 2.0 (3-6 years) (\$250,000/scientist year).
 - Priority: medium term.
 - Additional resources: \$250,000.

8. Integrated systems approach to multiple pest control in vegetable and other annual cropping systems. With the loss of methyl bromide, short-term crop pest control strategies will involve the combined use of several target-specific pesticides including nematocides, fungicides, insecticides, and herbicides. Temporal integration of pesticide use practices and incorporation of new technologies and enhancement of existing technologies needs to be investigated to minimize production costs and losses due to soil-borne pests and disease. In this context, expanded label registrations and modes of application are also likely to be required.

- Scientists/year: 2.0 (3-5 years) (\$250,000).
- Priority: medium term.
- Additional resources: \$300,000.

9. Assessment of the long-term economic impacts of phasing out fumigation uses of methyl bromide in U. S. agriculture. Current assessments of banning or phasing out methyl bromide have only attempted to account for the short-term, single crop economic impacts. Costs and benefits associated with combined use of one or more alternative pesticides are needed on the various cropping systems and multiyear streams of profits also need to be developed and analyzed. Changes in farmworker labor requirements as well as the effect on agricultural employment and the ripple effect into the private sector need to be elaborated. Noncompliance and continued use of methyl bromide by other foreign agricultural producers, including impacts on free trade agreements on U. S. agriculture, also require further investigation.

- Scientists/year: 2.0 (2-3 years).
- Priority: near term-immediate start is needed.
- Additional resources: \$100,000.

Postharvest/Quarantine

1. Significant research will be needed to bring the available residual protectant materials (malathion, actellic, reldan, Bt, pyrethrum, diatomaceous earth) to the point where they could substantially reduce fumigant use.

- Scientists/year: 6.0 (5-8 years) (\$250,000/scientist year).
- Priority: medium term, but must begin immediately.
- Additional resources: \$300,000.

2. Several new-generation chemicals such as chitin inhibitors, insect growth regulators, protease inhibitors, and hormone inhibitors/mimics show promise as being much safer alternatives to either fumigants or the currently used protectants. These compounds tend to be highly specific toward insects, and thus highly desirable for food protection.

- Scientists/year: 5.0 (10-plus years) (\$250,000/scientist year).
- Priority: long term.
- Additional resources: \$500,000.

3. Conduct basic research on pest biology to ascertain activity sites for applications of new classes of chemical fumigants. This research may indicate new classes of chemical fumigants for quarantine applications.

- Scientists/year: 2.0 (5 plus years) (\$250,000/scientist year).
- Priority: long term.
- Additional resources: \$300,000.

4. Conduct basic research on growth regulators, such as methoprene, to determine the efficacy and application methods to be sure that such growth regulators will not quarantine security standards.

- Scientists/year: 2.0 (5 plus years) (\$250,000/scientist year).
- Priority: long term.
- Additional resources: \$300,000.

5. Research for replacement fumigants will not be extensive because few materials are available or likely to be developed. Research will likely focus on phosphine. Many possible alternatives for commodity treatment uses were screened from the 1940's to the 1980's. This research is still valid and only a very limited number of chemical fumigant compounds such as hexamethyl di-tin, methyl and ethyl formate, and acetaldehyde were investigated. These data should be reevaluated to determine if further investigation is warranted.

- Scientists/year: 3.0 (2-3 years) (\$250,000/scientist year).
- Priority: medium term.
- Additional resources: \$100,000.

VI. Nonchemical Alternatives Research

Introduction

Researchers have been working on biological control of pests for more than 20 years and have yet to find acceptable alternatives. Thus research/development programs will end much later than the year 2000 and will require significant commitment of research funds and human resources. Most of the following technologies are in the very formative stages. None of these technologies, as yet, have been ranked according to their potential, research to be done, or practical applicability.

Host Plant Resistance

Host plant resistance appears to be the most effective biologically based strategy for managing plant pests. Host plant resistance can be genetically based or it can be included with biological agents. Genetic resistance can be achieved by:

- Conventional breeding and selection of valuable traits.
- Use of tissue culture and selection of explants and somaclonal variants.
- Development of transgenic plants.

Use of host resistance, particularly in the production of nursery stock, raises the concern and danger of symptomless carriers of disease and insect pests. Such vectors may spread pests from nurseries to the end user—forests, farms and urban landscapes. All of these approaches are long term. In addition, pest resistance genes have, for the most part, not been identified, located, and isolated for manipulation.

Microbial Biological Control

Microbial biological control agents are available to control a few pathogens. Fungal antagonists are known that have activity against some plant pathogenic fungi and plant parasitic nematodes. Bacterial antagonists have been identified for use against some plant pathogenic fungi and plant parasitic nematodes. Predacious nematodes can be used against insects and parasitic nematodes. Avirulent strains of plant pathogenic fungi and bacteria have been successful on a species by species basis in a few cases—for example, saprophytic *Fusarium* vs. pathogenic *Fusarium*, antagonistic *Pseudomonas* vs. pathogenic *Pseudomonas*, and *Agrobacterium radiobacter* vs. *Agrobacterium tumefaciens*. Additional experimental biocontrol agents that have not achieved practical success in nematode management, but that have shown success in specific instances on specific pathogens in specific locations, include bioattractants, nematode sex pheromones, and nematode hatching control agents. Microbial approaches to pest control are largely undeveloped and will require several years of research for large-scale implementation.

Noncultural Technologies

Noncultural technologies include heat—steam—which is useful for greenhouse and small-scale applications in the United States, but is not applicable for large fields. Organic matter (sewage sludge) can be used in limited cases to increase soil organic matter to improve soil tilth and enhance crop resistance to disease. In large areas of sandy soils, however, this becomes impractical.

Cultural Technologies

Cultural practices include crop rotation with antagonistic plants and cover crops to suppress some weeds. However, nutsedge is resistant to most allelopathic treatments. Fallow and intermittent tilling of soils during hot, dry conditions for control of nematodes and deep plowing for control of fungi can be used; however, the impact on the physical structure of the soil is often detrimental and the operation is expensive.

Plastic Mulch and Plant Residues

Tarp coverage of soil for weed control has been used with some success; however, in some areas nutsedge will grow through the plastic without any effect on the plants. In addition to plastic mulches, tropical legumes, crop residue, and pine straw have been used to control weeds in strawberries.

Soilless Media

In applications that restrict the quantities of soil required, such as transplant production (ornamentals, forestry, tobacco, and vegetables), soilless media are being developed in combination with EPA-registered biological control agents to control selective damping-off diseases.

Recommendations on Research Needs for Nonchemical Research

Soil Fumigation

1. Develop biological control technologies for Verticillium and Fusarium wilt (including interactions with nematodes) on many crops (eggplant, cucurbits, tomatoes, potatoes, forest trees, ornamentals, etc.). Develop biological control methods, using biological control agents singly or in combination with reduced levels of chemicals and cultural control practices for control of damping-off blights and fruit rots. Develop biological control technologies for Armillaria. Biological control of nematodes in production field situations has not and does not appear too promising, especially within the next 5 years.
 - Scientists/year: 5.0 (\$250,000/scientist year).
 - Priority: long term.
 - Additional resources: existing.
2. Develop biological control technologies to control plant-parasitic nematodes and to control soilborne fungal diseases, including:
 - Biological control technologies for replant problems with pome and stone fruits, with special emphasis on lesion nematode, Phytophthora, Pythium, Fusarium, Armillaria mellea, sting nematode, and root-knot nematodes.
 - Biological control technologies for southern blight, root-knot and lesion nematodes and damage caused by Sclerotium rolfsii, in peppers, carrots, and other field-grown vegetables.
 - Biological control agents for plant pathogenic fungi and nematodes on all types of transplants. Treatment of root ball with bio-control agents.
 - Scientists/year: 6.0 (\$250,000/scientist year).
 - Priority: medium term.
 - Additional resources: \$100,000/year.
3. Develop genetically engineered vegetable crops to introduce resistance to major pathogenic fungi and nematodes.
 - Scientist/year: 4.0 (\$250,000/scientist year).
 - Priority: medium term.
 - Additional resources: additional \$1 million specialized equipment.
4. Develop biological control agents for introduction into forest tree nursery seedbeds for control of damping-off fungi, Macrophomina phaseoli, Fusarium spp, Cylindrocladium cutworms, whitegrubs, and cranberry girdler.
 - Scientist/year: 3.0 (\$250,000/scientist year).
 - Priority: medium term.
 - Additional resources: available.

5. Develop fungi and insects destructive to weeds for biological control of major problem weeds, especially nutsedge and other difficult-to-control weeds.
 - Scientist/year: 1.0 (\$250,000/scientist year).
 - Priority: short term.
 - Additional resources: available.
6. Develop biological control of red stele, root-knot, and lesion nematodes in strawberries.
 - Scientists/year: 2.0 (\$250,000/scientist year).
 - Priority: medium term.
 - Additional resources: available.
7. Develop biological control technologies and organic amendments for increased resistance to summer patch, brown patch, dollar spot, and nematodes in turf and control of soilborne diseases in forest nurseries.
 - Scientists/year: 2.0 (\$250,000/scientist year).
 - Priority: medium term.
 - Additional resources: available.
8. Develop antagonistic micro-organisms that can be associated with plastic mulches to enhance antagonist activity towards pathogenic fungi and nematodes.
 - Scientist/year: 2.0 (\$250,000/scientist year).
 - Priority: medium term.
 - Additional resources: available.
9. Develop research programs on application of biological, cultural, and disease resistance technologies and strategies for use with Integrated Pest Management programs.
 - Scientists/year: 6.0 (\$250,000/scientist year).
 - Priority: medium term.
 - Additional resources: \$500,000 per year.
10. Initiate studies to elucidate the factors responsible for pathogen (fungi, nematodes, and bacteria) suppression which occur naturally in some soils known as “suppressive soils”, utilizing multidisciplinary team approaches.
 - Scientists/year: 3.0 existing plus 3.0 additional (\$250,000/scientist year).
 - Priority: long term.
 - Additional resources: existing.
11. Initiate research on understanding host/parasite relations in nematode and pathogen/host systems.
 - Scientists/year: 2.0 (\$250,000/scientist year).
 - Priority: long term.
 - Additional resources: existing.
12. Initiate studies on soil ecology of fungal pathogen and parasitic nematodes as well as antagonistic biological control agents.
 - Scientists/year: 2.0 (\$250,000/scientist year).
 - Priority: long term.
 - Additional resources: additional resources needed.

Postharvest/Quarantine

Depending on the type of treatment, many methods must be developed that are specific to given commodities. Often their influence on specific cultivars also will have to be determined. Many alternatives, by necessity, will require changes in handling, packing, and storage systems and will be more costly than methyl bromide. The more severe quarantine treatments may result in high levels of damage. The large volume of many commodities (55 million boxes of stone fruits from the San Joaquin Valley of California in 1992, for example) coupled with short storage life may exclude some alternative treatments, and many alternatives will have major impact on postharvest handling.

Most new quarantine treatments will require approval by each importing country. In addition to the protocols, no consideration has been given in this agenda to the time delays and problems associated

with certification of quarantine facilities at the shipping point. This often takes years to negotiate.

Quarantine Technology Descriptions

1. **Heat.** May be applied to a commodity as a hot water immersion or spray, vapor (moist), or dry air. Vapor heat and water immersion are suitable for fresh commodities and dry air for dried fruits, tree nuts, and grains. Limitations are the susceptibility of the commodities to heat damage and in the case of water immersion, water sorption, and slow damage. These methods require high energy input and require modification of processing facilities. Fluidized beds have been used for applications to grains.
2. **Cold.** Treatment is applied during storage and/or transit. This requires high energy input, moisture control, and close tolerances for quarantine. Fresh fruits and vegetables may be damaged and/or require relatively long treatment times. Treatment facilities must be constructed to allow for large volume turnovers of fruit and requires accurate monitoring through storage and shipping.
3. **Ionizing radiation (irradiation).** Irradiated products have usually been well received by the public, both in the United States and elsewhere. Efficacy generally is within approved dose levels. It is recognized that capital costs are high; however, the most significant factor is the effect of processing on the cost to the consumer. In recent large-scale processing of fruits and vegetables at an irradiation facility in Florida, products labeled "treated by irradiation" were shipped to stores in Florida and Chicago. The customers preferred the irradiated products, and in both cases the stores had trouble selling the nonirradiated produce. Some commodities or particular varieties are sensitive to treatment. Opportunities may exist for economical use of ionizing radiation treatments for quarantine treatment of commodities where there is a sufficient diversity of products to support the operation of the facility throughout the entire year. Grains are particularly suited to treatment with ionizing radiation.
4. **Controlled atmospheres.** Controlled atmospheres contain high levels of carbon dioxide or low levels (< 1.0 percent) of oxygen. Dried commodities have been successfully treated; however, fresh commodities present a problem of being sensitive to most treatments that kill insects. Existing facilities will generally require extensive modification to maintain these atmospheres; new facilities may be required. Applications at low temperatures (fresh fruits and vegetables) require long treatment times for efficacy.
5. **Microbials.** May be applied as a spray or dust to commodities. Cost is greater than methyl bromide and-for bulk commodities-must be applied at the time of storage. May provide long-term protection and avoid need for repeated fumigations. Quarantine use would be limited. Insects may develop resistance to some microbial biological controls.
6. **Parasites and predators.** Usually work best for reduction of pests, not eradication. Are released in storage facilities usually between seasons to reduce insect infestation of incoming new crops. Costs more than methyl bromide, but may reduce pest populations for long periods. However, exported products must be free of live insects.
7. **Phytosanitation and pest free certification.** Production areas are inspected visually or by trapping (pheromone traps, etc.). Production is located in areas of low insect population. Costs are large due to need for inspectors and packing plant certification for export marketing. Development is complex, but is a viable alternative for sensitive commodities and defined growing areas.

8. **Combination treatments.** Two or more insect control methods are applied simultaneously or serially to provide greater efficacy. An application of a virus to stored almonds may provide long-term protection after initial short-term treatment with a controlled atmosphere. Costs are usually increased. Data requirements will increase if used for quarantine.
9. **Systems approach.** More than two methods of insect control are used. As an example, sanitation to reduce insect contamination is followed by selective harvest and/or grading to further reduce insect infestation followed by an insecticide application to reduce insects to a tolerable level. This system may be used to protect commodities from further infestation during marketing. However, each treatment phase adds costs, more processing equipment is needed, and each component must be certified by quarantine regulators.
10. **Insect-resistant packaging.** Packaging developed to contain controlled atmospheres or to prevent insect reinfestation of product during marketing.
11. **Protectants.** Insecticides developed to protect commodities during postharvest storage and in marketing system, including repellants, anti-feedants, etc.
12. **Impact technology.** Mechanical impact methods for disinfesting grains and seeds.

Recommendations on Research Needs for Nonchemical Quarantine Research

Propagative Plant Material and Cut Flowers. Heat treatments will depend on tolerance of plant species. In many cases, it is possible that nursery stock could be inspected and determined to be pest free. Pheromones could be used for detection but likely would not provide a means of disinfestation. Insecticide dips may also be a possibility.

1. Heat treatments.
 - Scientists/year: 1.0 (\$250,000/scientist year).
 - Priority: Short term.
 - Additional resources: estimates not available.
2. Inspection systems (with remote monitoring facility) and pheromone traps.
 - Scientists/year: 1.0 (\$250,000/scientist year).
 - Priority: short term.
 - Additional resources: estimates not available.
3. Phytosanitation and certification/pest free status.
 - Scientists/year: 1.0 (\$250,000/scientist year).
 - Priority: short term.
 - Additional resources: estimates not available.

Green Leafy Vegetables. Many are probably sensitive to heat treatments. Since they are often placed in cold storage, specific cold treatments are likely to be more successful.

1. Pest free status.
 - Scientists/year: 1.0 (\$250,000/scientist year).
 - Priority: medium term.
 - Additional resources: estimates not available.
2. Cold treatments.
 - Scientists/year: 1.0 (\$250,000/scientist year).
 - Priority: medium term.
 - Additional resources: estimates not available.

3. Nonhost status and genetic resistance.
 - Scientists/year: 1.0 (\$250,000/scientist year).
 - Priority: medium term.
 - Additional resources: estimates not available.

Root Vegetables. Heat or cold treatments could be put in place in a relatively short period of time.

1. Controlled atmosphere.
 - Scientists/year: 1.0 (\$250,000/scientist year).
 - Priority: short term.
 - Additional resources: estimate not available.
2. Heat and cold treatments.
 - Scientists/year: 2.0 (\$250,000/scientist year).
 - Priority: short term.
 - Additional resources: estimates not available
3. Packing house processing.
 - Scientists/year: 1.0 (\$250,000/scientist year).
 - Priority: short term.
 - Additional resources: estimates not available.

Dried Fruits and Nuts. These high-value commodities are amenable to many different treatments such as heat, cold, and controlled atmospheres. Microbial and biocontrol agents may provide long-term protection. Integrated systems also could be developed. All would require major change in commodity handling. Irradiation has been shown to be effective.

1. Systems approach.
 - Scientists/year: 3.0 (\$250,000/scientist year).
 - Priority: long term.
 - Additional resources: estimates not available.
2. Heat and cold treatments.
 - Scientists/year: 1.0 (\$250,000/scientist year).
 - Priority: medium term.
 - Additional resources: estimates not available.

3. Microbials and biocontrol.
 - Scientists/year: 3.0 (\$250,000/scientist year).
 - Priority: long term.
 - Additional resources: estimates not available.
4. Controlled atmosphere.
 - Scientists/year: 1.0 (\$250,000/scientist year).
 - Priority: short term
 - Additional resources: estimates not available.
5. Combination treatments.
 - Scientists/year: 1.0 (\$250,000/scientist year).
 - Priority: medium term.
 - Additional resources: estimates not available.
6. Irradiation.
 - Scientists/year: 0.5 (\$250,000/scientist year).
 - Priority: short term.
 - Additional resources: most research complete, remaining issues are regulatory.
7. Physical.
 - Scientists/year: 1.0 (\$250,000/scientist year).
 - Priority: short term.
 - Additional resources: estimates not available.

Tropical Fruit. Heat treatments have been developed for several commodities, but many others need to be developed. May not tolerate cold treatment. Irradiation has been studied and should be useful for some commodities and available in a short time. Logistical problems may be abundant regardless of treatment selected. May be amenable to systems approach.

1. Heat and cold.
 - Scientists/year: 12.0 (\$250,000/scientist year).
 - Priority: short term.
 - Additional resources: estimates not available.

2. Irradiation.

- Scientists/year: 1.0 (\$250,000/scientist year).
- Priority: short term.
- Additional resources: technology available.

3. Pest-free areas (including IPM to reduce populations).

- Scientists/year: 1.0 (\$250,000/scientist year).
- Priority: long term.
- Additional resources: estimates not available.

4. Nonhost status.

- Scientists/year: 1.0 (\$250,000/scientist year).
- Priority: medium term.
- Additional resources: estimates not available.

5. Systems approach.

- Scientists/year: 1.0 (\$250,000/scientist year).
- Priority: long term.
- Additional resources: estimates not available.

6. Shrink wraps and coatings.

- Scientists/year: 1.0 (\$250,000/scientist).
- Priority: medium term.
- Additional resources: estimates not available.

Deciduous Fruits and Berries. Many treatments may be plant-species specific. Cold and heat treatments have been developed for some; often these will be cultivar specific. Irradiation has been researched, but will be costly. May be amenable to systems approaches.

1. Heat and cold treatments.

- Scientists/year: 4.0 (\$250,000/scientist year).
- Priority: short term.
- Additional resources: estimates not available.

2. Nonhost status.

- Scientists/year: combine with citrus commodities.
- Priority: medium to long term.
- Additional resources: see citrus recommendations.

3. Processing.

- Scientists/year: 1.0 (\$250,000/scientist year).
- Priority: medium to long term.
- Additional resources: estimates not available.

4. Controlled atmosphere (apples-pears).

- Scientists/year: 1.0 (\$250,000/scientist year).
- Priority: medium to long term.
- Additional resources: estimates not available.

5. Irradiation.

- Scientists/year: 1.0 (\$250,000/scientist year).
- Priority: short term.
- Additional resources: technologies available.

6. Systems approach.

- Scientists/year: link with citrus research.
- Priority: medium to long range.
- Additional resources: estimates not available.

Citrus. Citrus is commonly stored in cold temperatures. Heat treatments, depending on method of application and cultivar, are promising. Nonhost status and systems approach could be combined with the above. Pest-free zones have been used in Florida. Irradiation has been extensively studied and is clearly in contention as a substitute.

1. Heat and cold treatments.

- Scientists/year: 6.0 (\$250,000/scientist year).
- Priority: short term.
- Additional resources: \$100,000/year.

2. Nonhost status and systems approach.

- Scientists/year: 1.0 (\$250,000/scientist year).
- Priority: medium term.
- Additional resources: \$50,000.

3. Pest-free areas.

- Scientists/year: 1.0 (\$250,000/scientist year).
- Priority: medium to long range.
- Additional resources: \$100,000.

4. Irradiation.

- Scientists/year: 1.0 (\$250,000/scientist year).
- Priority: short term.
- Additional resources: technology readily available.

Grains, Peanuts, Legumes, and Beans. Generally amenable to most alternative treatments. Biological control agents need further investigation.

1. Heat and cold treatments.

- Scientists/year: 2.0 (5 years) (\$250,000/scientist year).
- Priority: medium term.
- Additional resources: \$5,000 (High costs, because each commodity must be individually adapted.)

2. Controlled atmosphere.

- Scientists/year: 2.0 (5 years) (\$250,000/scientist year).
- Priority: medium term.
- Additional resources: \$50,000.

3. Systems approach.

- Scientist/year: 4.0 (5 years) (\$250,000/scientist year).
- Priority: medium to long term.
- Additional resources: estimates not available.

4. Impact technology.

- Scientists/year: 0.5 (\$250,000/scientist year).
- Priority: short term.
- Additional resources: \$500,000.

5. Irradiation for export.

- Scientists/year: 0.5 (\$250,000/scientist year).
- Priority: short term.
- Additional resources: in use commercially little need for additional research.

6. Parasites and Predators.

- Scientists/year: 4.0 (5 years) (\$250,000/scientist year).
- Priority: medium term.
- Additional resources: \$100,000.

7. Microbials.

- Scientists/year: 2.0 (5 years) (\$250,000/scientist year).
- Priority: long term.
- Additional resources: \$200,000.

Melons and Fruits Eaten as Vegetables. Irradiation, cold, and heat treatments provide the most promise. A commercial irradiator is available in Florida. Tolerance to heat and cold treatments may be narrow and probably cultivar specific.

1. Irradiation.

- Scientists/year: 1.0 (\$250,000/scientist year).
- Priority: medium term.
- Additional resources: technology is available.

2. Heat and cold.

- Scientists/year: 2.0 (\$250,000/scientist year).
- Priority: medium term.
- Additional resources: \$50,000.

3. Nonhost status.

- Scientists/year: 1.0 (\$250,000/scientist year).
- Priority: medium term.
- Additional resources: \$100,000.

Nonfood (tobacco, packing material, wood products)

1. Heat and cold.

- Scientists/year: 1.0 (\$250,000/scientist year).
- Priority: short term.
- Additional resources: estimates not available.

2. Water immersion (logs) - salt ocean water soaking.

- Scientists/year: 1.0 (\$250,000/scientist).
- Priority: medium term.
- Additional resources: estimates not available.



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